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A review of the scientific literature was undertaken with a view to defining test parameters and criteria for dead space in respiratory protective equipment. Considerable differences were found between the performance requirements specified by existing standards, and some appeared to be unrepresentative of industrial conditions. The test parameters specified by some draft European standards, in particular, represented a workrate level which was considered extreme in relation to many industrial activities. It was proposed that these limitations could be overcome by the adoption of test parameters based on realistic levels of industrial workload. A set of parameters derived from a draft ISO classification of metabolic rates was suggested as one possible approach.

Performance criteria were also examined. The inhaled air limit of 1% CO_2, adopted by many standards, was found to be amply supported by scientific data. Although limit values of 1.5 to 2% were specified in some standards, these were considered unsuitable for industrial RPE.

1. INTRODUCTION

1.1 Dead space effects in respiratory protective equipment

One of the more important functions of respiratory protective equipment (RPE) standards has been to ensure that devices do not impose an excessive physiological burden upon the wearer. High levels of strain may lead to operator fatigue or, where other environmental stressors exist, to acute health damage.

A review of the literature by LOUHEVAARA (1984) found that the re-breathing of carbon dioxide due to added dead space was a potential source of strain in RPE. In physiological terms, dead space can be defined as the volume of the airway in which there is no significant exchange of oxygen and carbon dioxide (COMROE, 1974).

Wearing a respirator face mask or mouthpiece increases the physiological dead space and hence the volume of the previous exhalate (with high carbon dioxide content) which is re-inhaled with each breath. The increased inhaled carbon dioxide levels which result from this effect lead to both increased lung ventilation and the retention of carbon dioxide in the lungs (JAMES, 1976; DAHLBACK and FALLHAGEN, 1987). Initially the RPE wearer may only be aware of increased breathing effort but as inhaled carbon dioxide levels increase, the ability to compensate through hyperventilation diminishes, leading to the onset of adverse physiological reactions and symptoms. Limits must therefore be set for inhaled carbon dioxide in respirators if adverse health effects are to be avoided (JAMES, 1976).

A number of factors influence the dead space imposed by a respirator face mask. The design of the mask in terms of its internal volume, the location of openings and the paths of air into and out of the device, all have an influence on the dead space effect (KLOOS and LAMONICA, 1966). It is important to recognise that not all the dead space volume within the face mask is re-breathed. The volume closest to the mouth and nose will be, but there may also be static pockets of air around the edge of the facepiece. On this basis one can distinguish an effective dead space from the geometric dead space, the latter being the actual volume of the facepiece cavity. Physiological effects are dependent upon the effective dead space and it is this parameter which is evaluated either directly or indirectly (through inhaled carbon dioxide levels) in standard test methods.

Re-breathing of carbon dioxide may also occur in other types of respiratory protective equipment. For example, air fed hoods and blouses have a relatively large dead space volume (BENTLEY, 1980) which, if not adequately ventilated, permits accumulation of exhaled carbon dioxide. As might be expected, failure of the air supply may have particularly serious consequences in such equipment, particularly if there is no emergency breathing device.

In closed circuit breathing apparatus, the carbon dioxide absorber has a limited lifespan and when this is exhausted carbon dioxide may pass into the inhaled air (KLOOS and LAMONICA, 1966; BENTLEY, 1980). Again, standards have been established to limit physiological strain due to carbon dioxide inhalation in apparatus wearers.

Carbon dioxide accumulation may also pose problems in non-respiratory protective equipment. All-enclosing hoods or helmets with inadequate ventilation may result in high inhaled carbon dioxide levels, a factor that is often missed during equipment testing (ALDMAN *et al*, 1981; REISCHL and REISCHL, 1978).

1.2 Standard test methods

A number of standard test protocols are available for assessing effective dead space in RPE. These seek to ensure that inhaled carbon dioxide levels will be within acceptable limits in devices which comply with the standard.

Given the multiplicity of factors which determine the effective dead space in RPE, it is important that standard test methods are based on realistic usage conditions. For example, in air fed hoods, the rate of carbon dioxide accumulation is dependent upon the wearer's carbon dioxide output. As the latter depends on the wearer's workrate it is important that the test parameters should reflect the range of workrates encountered during hood operations.

In practice it is found that published test methods vary considerably in terms of the conditions imposed. Some methods are based on resting levels of activity while others represent maximal work output. This review, through evaluation of published data seeks to establish a physiological rationale for test methods. This involves defining the range of workrates and corresponding respiratory parameters for a range of industrial activities.

Performance criteria too, must be given further consideration. In the case of draft CEN (Comite Europeen de Normalisation) RPE standards a criterion of 1% inhaled carbon dioxide is applied and this appears to be supported by physiological evidence. However, limits of 1.5 to 2.5% have been applied in both British and American standards. By way of contrast carbon dioxide levels in workroom air are frequently limited to 0.5%. A reappraisal of carbon dioxide tolerance data is therefore timely, thus providing a scientific basis for the discussion of performance criteria.

2. TEST METHODS AND CRITERIA

2.1 Geometric dead space

While it has been shown that it is the effective dead space which determines the extent of re-breathing (RITTER, 1966), some authors have measured geometric dead space in order to obtain a predictor of physiological effects. KLOOS and LAMONICA (1966), for example, described a water displacement method for measuring the internal volume of breathing apparatus facepieces (full face masks). After sealing the valves, the facepieces were fitted to an anthropometric dummy head and water injected into the facepiece cavity. The volume required to fill this space was taken as the geometric dead space volume. A similar method, using small glass beads instead of water, was described by LOUHEVAARA *et al* (1984).

While this approach may be acceptable for half masks where most of the internal volume is re-breathed, it is less satisfactory for full masks (without an inner orinasal cup). In the latter case, the effective dead space may differ considerably from the geometric dead space, the former being a complex function of the respiratory frequency, tidal volume and exhaled carbon dioxide concentration (RITTER, 1966). Geometric dead space would also be an inappropriate predictor of dead space effects in air fed devices.

2.2 Effective dead space and inhaled carbon dioxide levels

2.2.1 Machine test methods

2.2.1.1 *Test parameters*

Published breathing machine test methods for inhaled carbon dioxide levels in RPE are generally similar in principle but differ considerably in terms of the test parameters. The device under test is usually fitted to a dummy head (and torso in the case of an air fed blouse or suit), the latter being connected to a breathing machine with sinusoidal airflow characteristics. A constant exhaled carbon dioxide level is achieved either by injecting pure carbon dioxide into the airstream (usually on the inhalation side of the circuit) or by feeding the machine from a standard carbon dioxide-air mixture in a reservoir. The machine is set to give a specified number of breathing cycles at a fixed stroke volume and the test is run until a steady state is achieved. Inhaled carbon dioxide levels are generally determined from samples withdrawn in the immediate vicinity of the mouth or nose, or from a mixing chamber placed in the inhalation side of the breathing circuit.

In standard test methods the tidal or stroke volume, breathing rate and exhaled carbon dioxide concentration are specified for the device under test. There are considerable differences between published test methods in this respect however. The extent of this variation can be seen in Table 1 which summarises test methods and criteria from various standards and research publications.

Table 1 Comparison of Machine Test Parameters.

SOURCE AND DATE	TYPE OF RPE	BREATHING MACHINE SETTINGS: Respiratory Minute Volume ($l\ min^{-1}$)	Tidal Volume (l)	Respiratory frequency (min^{-1})	Exhaled CO_2 (%)	INHALED CO_2 LIMIT (%)
(a) <u>Standards</u>						
COMITE EUROPEEN DE NORMALISATION -						
Draft Standard Specifications						
prEN 136 (Nov. 1987)	Full face masks.	50	2	25	5	1
prEN 140 (Mar. 1987)	Half and quarter masks.	"	"	"	"	1
prEN 145 (Aug. 1987)	Self-contained closed circuit breathing apparatus (compressed oxygen type).	30	1.5	20	4.5*	1 (facepiece) 1.5 (mouthpiece)
		40	2	20	5*	
		50	2	25	5*	
prEN 146 (Oct. 1986)	Powered particle filtering devices incorporating helmets or hoods.	50	2	25	5	1
prEN 149 (Mar. 1987)	Filtering half masks to protect against particles.	"	"	"	"*	"
prEN 270 (Sept. 1989)	Compressed air line BA incorporating a hood.	"	"	"	"*	"

Table 1 Contd.

SOURCE AND DATE	TYPE OF RPE	BREATHING MACHINE SETTINGS Respiratory Minute Volume (l min^{-1})	Tidal Volume (l)	Respiratory frequency (min^{-1})	Exhaled CO_2 (%)	INHALED CO_2 LIMIT (%
BRITISH STANDARDS INSTITUTION						
Standard Specifications for Breathing Apparatus BS 4667						
Part 1: 1974	Closed circuit BA.	40	2	20	5*	0.75% average with maximum excursion to 1%. 2% limit when into reserve
		100			5*	
Part 2: 1974	Open circuit BA.	40	2	20	5*	1.5
		80	2.5	32	5*	1.5
Part 3: 1974	Fresh air hose and compressed airline BA.	40 80 100	2 2.5 3	20 32 33.3	5* 5* 5*	1 (mouthpiece 1.5 (facepiece/half mask
Part 4: 1982	Escape BA.	40 80 100	2 2.5	20 32	5* 5* 5*	Variable according to set's working duration. Ranging from 4% at 5 mins to 1.5% at 30 mins
BRITISH STANDARDS INSTITUTION		30	1.5	20	4.5*	3
Draft Standard Specification (1985)	Fire escape respirators.					

Table 1 Contd.

SOURCE AND DATE	TYPE OF RPE	BREATHING MACHINE SETTINGS				INHALED CO_2 LIMIT (%)
		Respiratory Minute Volume ($l\ min^{-1}$)	Tidal Volume (l)	Respiratory frequency (min^{-1})	Exhaled CO_2 (%)	
(b) **Published papers**						
Kloos and Lamonica (1966)	Self-contained BA.	10.5	0.73	14.5	5	2 (average level)
Bernard *et al* (1979c)	Closed circuit self-contained BA.	26	N	N	3.5*	Criteria specified in terms of time to CO_2 breakthrough.
		37	N	N	3.5*	
		48	N	N	3.5*	
Ritter (1966)	Full and half masks.	15 30 50	1 1.5 2.0	15 20 25	Range of exhaled CO_2 concentrations used to investigate dead space properties.	No criteria specified.
Wagner (1987)	Closed circuit self-contained BA.	30	N	N	Variable depending on minute ventilation, range 4-5%*.	No criteria specified.
		40	N	N		
		50	N	N		
Bostock (1985)	Positive pressure powered dust hoods and blouses.	40	2	20	5	1
Morrison (1988) (proposed test procedures for diving equipment)	Underwater breathing apparatus.	15 22.5 40 62.5 75	1 1.5 2 2.5 2.5	15 15 20 25 30	4 " " " "	Average inhaled concentration <1 (preferred) 2 (maximum)

* exhalate saturated with water vapour at 37°C.
N parameter not specified in source document.1

Respiratory minute volumes (sinusoidal flow rates) show the most marked variation. They range from 10.5ℓ min^{-1} representing sedentary conditions through to 100ℓ min^{-1} representing maximal physical workload. The specified tidal volulmes appear to be scaled to the respiratory minute volumes and range from 0.73 to 3.3ℓ. Corresponding breathing rates range from 14.5 to 33 cycles per minute.

The variation in test parameters partly reflects the differences in performance specifications for the various types of RPE. For example, breathing apparatus is often used for physically demanding firefighting or rescue tasks where air consumption by the wearer may exceed 80ℓ min^{-1} (BENTLEY, 1980). The respiratory minute volumes (up to 100ℓ min^{-1}) specified in the relevant parts of BS 4667 therefore allow for the greater respiratory demands likely to be made on such apparatus. It is interesting to note that minute volumes do not exceed 50ℓ min^{-1} in the draft European Standards.

The sedentary conditions specified by KLOOS and LAMONICA (1966) appear to be atypical when compared with other breathing apparatus standards. The authors selected their test parameters on the grounds that the low breathing rate gave the greatest concentration of carbon dioxide in the inspired air. It was argued that since the apparatus dead space was a fixed volume, any increase in the tidal volume would dilute the carbon dioxide in the dead space and hence give lower inhaled levels. The work of RITTER (1966) and of CUMMINGS *et al* (1960) shows however that the effective dead space of a face mask increases with tidal volume as the wearer works harder. The demands upon carbon dioxide absorbents will also increase at higher workrates. A 'sedentary' test is therefore unlikely to give an adequate indication of inhaled carbon dioxide levels under operational conditions.

The published standards show less variation in respect of exhaled carbon dioxide levels, a 5% challenge concentration being a common choice. While this level is appropriate at high workrates, the average exhaled concentration may be closer to 4% at light workrates (WAGNER, 1987).

The principle of linking test parameters to RPE wearers' workrates is discussed in several of the published papers. The test parameters described by WAGNER (1987), for example, were based on respiratory measurements obtained from mineworkers undertaking simulated mining tasks and emergency escape activities. Similarly the test parameters proposed by MORRISON (1988) for underwater breathing apparatus were based on measured workrates (and other respiratory parameters) for a wide range of diving activities.

In both the above methods devices were tested at a number of machine settings corresponding to graded workrate levels. This would seem to be a sensible approach given the complex interrelationships between the various respiratory parameters and their effects on the effective dead space (RITTER, 1966).

2.2.1.2 *Test criteria*

It can be seen from Table 1 that there are differences between the test methods in respect of limits established for inhaled carbon dioxide. An average level of 1% carbon dioxide in the inhaled air is specified in all the draft European Standards with the exception of prEN 145 where a level of 1.5% is permitted for apparatus fitted with a mouthpiece. The 1% criterion is also called up in Parts 1 and 3 of BS 4667.

Criteria in the range 1.5 to 4% have been established for emergency escape devices where the wearer is exposed to elevated carbon dioxide concentrations for a relatively short time (less than 30 minutes). Such levels may be tolerated, albeit with some physiological strain (see Chapter 4) for a short time but would clearly be inappropriate for devices in everyday use.

It is clear that different rationales have been adopted in setting the various criteria listed in Table 1. Factors such as the type of device, the expected duration of use and the wearer's workrate would all seem to have some bearing on the physiological limit for carbon dioxide inhalation. These factors are considered in more detail in Chapter 4.

2.2.2 Man tests

It has been argued (e.g. DAHLBACK and FALLHAGEN, 1987) that wearer tests give a more realistic assessment of the effects of respirator dead space. A number of test protocols are described in the literature but these, like the machine tests, show considerable variation in terms of the conditions adopted.

One of the earliest published methods was developed in 1918 by the US Chemical Warfare Service (cited by CUMMINGS *et al*, 1960). In this protocol for military gas masks, the wearer was required to hold his breath at the end of an exhalation. A known volume of air was then flushed through the mask and the collected wash air analysed. The effective dead space was then derived, this being the volume of expired air which remained to be inhaled with the next breath.

More recently, rapid response infra-red analysers and respiratory mass spectrometers have made possible breath-by-breath analyses of carbon dioxide levels in masks and hoods. MICHEL *et al* (1969), for example, measured carbon dioxide levels in air ventilated space suits. End-inspired carbon dioxide levels were determined by mass spectrometry in suit wearers undertaking treadmill workloads. The workloads were individually calibrated for each subject so that measurements could be undertaken at fixed metabolic rates (in the range 65 to 456 Wm^{-2}. Criterion levels of 1% and 2% were established for 'nominal' and 'emergency' conditions, respectively.

It was found, not surprisingly, that breathing zone carbon dioxide concentrations increased in proportion to the wearer's metabolic rate. While carbon dioxide concentrations could be reduced to the 1% level by increasing the suit flow rate, this was less effective at high metabolic rates (>325 Wm^{-2}).

COMTE (1972), measured breathing zone carbon dioxide concentrations in wearers of self contained breathing apparatus and a variety of air fed equipment. The protocol involved 30 minutes cycling at 50 W, followed by a 10-minute bout at 100 W. Carbon dioxide levels again increased with the wearer's workrate, ranging from 0.25% at rest to a peak value of 1.6% at 50 W. At 100 W there was some evidence of an increase in arterial carbon dioxide levels.

LEERS (1972) compared the physiological effects of a full face mask with an experimental dead space (split plastic tube). The protocol involved a 75 W bicycle ergometer workload (duration not specified) preceded by a rest period. Respiratory and blood gas parameters were recorded under steady state conditions. Breathing zone carbon dioxide concentrations were not measured directly but were estimated from an empirical formula based on the effective dead space:tidal volume ratio.

The results showed that there was considerable inter-subject variation in effective dead space and hence in the ventilatory responses to the mask or the tube. A mask with a given geometric volume could therefore have widely differing effects on a panel of wearers depending on individual breathing patterns.

WHITE *et al* (1975) used workloads calibrated in terms of the subject's physical work capacity in their study of the effects of wearing a welding helmet with a dust respirator. Steady state bicycle workloads were set at one-third of the subject's physical work capacity (range 60-100 W for six subjects tested). The physiological effects of the apparatus dead space were found to be greater during exercise than at rest, all six subjects showing elevated arterial carbon dioxide tensions.

ALDMAN *et al* (1981) measured inhaled carbon dioxide levels in motorcyclists' crash helmets (fitted with full visor) during rest and exercise (50 W). This workload level was based on workrate data for road cruising. Even at rest, mean carbon dioxide concentrations exceeded 1.0%, rising to a maximum of 2.6% at 50 W. Inhaled levels during work were generally greater than resting levels (difference ~ 0.3 to 0.5% CO_2).

COMTE and KORADECKA (1981) examined inhaled carbon dioxide levels in an air fed hood and helmet and in full and half mask gas respirators. The test protocol included two 15-minute periods of bicycle ergometer exercise at 48 and 96 W respectively. A limiting criterion of 0.4% inhaled carbon dioxide was applied.

In the air fed devices, inhaled carbon dioxide concentrations were all less than 0.3% during the 48 W workload for flow rates in the range 100 to 200ℓ min^{-1}. When the workload was increased to 96 W, however, inhaled concentrations were in the range 0.4 to 0.53%. At the latter workrate there was also a marginal increase in the wearer's alveolar carbon dioxide tension to 47 mm Hg*.

Detailed results were not given for the filtering devices. It was stated, however, that half masks with a geometric dead space of less than 150 W gave inhaled levels of the order of 0.2%. In full masks with a geometric dead space of 400 W, inhaled levels were in the range 0.5 to 0.55%. Wearers of full masks again exhibited slightly elevated alveolar carbon dioxide tensions (~ 48 mm Hg)*.

A recent study by DAHLBACK and FALLHAGEN (1987) compared the results of wearer tests with those obtained using the CEN machine test (prEN 140). Two rubber half masks and a filtering facepiece were examined in the tests.

Carbon dioxide concentration was measured throughout the breathing cycle in each of the wearer tests, a respiratory mass spectrometer being used for this purpose. Lung volume changes were also measured by respiratory inpedance plethysmography. The exercise protocol involved hand-cranking for three minutes at 50 W, preceded and followed by five-minute rest periods.

Mean inhaled carbon dioxide levels were, without exception, greater during the wearer tests than in the corresponding machine test. The greatest discrepancy between the machine and wearer test results was found for the filtering facepiece. When tested by the CEN 140 method a mean inhaled CO_2 concentration of 0.5% was obtained. The wearer test gave an inhaled level of 1.2%, however.

The authors advanced two possible explanations for this difference. Firstly, it was noted that the tidal volume in the machine test (2ℓ) was about twice that observed in the subjects. Allowing for the fact that respiratory parameters would not have reached a steady state within the three-minute work period, the effective dead space to tidal volume ratio would have been greater in the wearer test. According to LEERS (1972) this would result in a higher inhaled carbon dioxide concentration being obtained in the wearer test.

Another possible explanation was that the machine test made use of a fan to blow away the carbon dioxide cloud in front of the respirator. In the case of a filtering facepiece which has no valve, a wearer could draw in a portion of this cloud, particularly under conditions of little or no ambient air movement.

In summary it can be stated that the wearer test protocols show considerable differences in terms of workloads and the parameters measured. Workload is clearly an important factor, a number of the studies showing the influence of the wearer's metabolic rate on the inhaled carbon dioxide levels. In some studies, e.g. ALDMAN *et al* (1981), there has been a deliberate attempt to simulate occupational

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* These values lie just beyond the normal range (35-45 mm Hg) and it is unlikely that clinical symptoms would have arisen (LANPHIER and CAMPORESI, 1982).

workloads whereas in others the selection criteria are undefined. The workloads in most of the protocols fall within the range 50 100 W (external workload), however, and this would equate with metabolic rates within the normal industrial range (ASTRAND and RODAHL, 1977).

While wearer tests appear to have an advantage over machine tests in allowing physiological effects to be monitored directly, in practice it would be difficult to ensure standardization of test conditions between test houses. The carbon dioxide output of a wearer undertaking a test protocol varies, depending on physical work capacity. In addition, parameters such as tidal volume and respiratory frequency would differ between subjects undertaking the same workload. On these grounds, wearer test protocols are probably unsuitable for RPE standards where it is necessary to establish a reproducible index of performance.

2.3 Specification of a standard test method

Having reviewed the various machine and wearer test protocols it is possible to define certain requirements for a standard machine test method.

Firstly, given the observed relationship between the wearer's workrate and inhaled CO_2 levels in RPE, test parameters must be scaled to appropriate metabolic rate levels. This requirement has not always been met in previously published methods. The test parameters adopted in the draft European Standards (minute ventilation 50ℓ min^{-1}, 5% CO_2 in exhalate), for example, correspond to a metabolic rate of circa 440 Wm^{-2}. This level is defined at 'very high' by ISO 7243 (INTERNATIONAL ORGANISATION FOR STANDARDISATION, 1982) and can be considered atypical of modern industrial conditions (ASTRAND and RODAHL, 1977).

Furthermore, since in some face masks inhaled CO_2 levels depend on the dead space to tidal volume ratio it would be appropriate to test devices at more than one machine setting. This would require that the machine tidal volume and exhaled CO_2 concentration were scaled to the minute volume. This is clearly shown in the parameters selected by MORRISON (1988) for underwater diving equipment (see Table 1).

The advantage for the user would be that the suitability of devices could be assessed for various workrate levels and, if necessary, a workrate restriction could be placed on the use of a particular device. The derivation of appropriate test settings is considered further in Chapter 3.

3. DERIVATION OF BREATHING MACHINE TEST PARAMETERS FROM PHYSIOLOGICAL DATA

3.1 Test parameters

In Chapter 2 it was argued that machine test parameters should be based on realistic levels of metabolic rate for industrial tasks. This section examines the available physiological data and shows how it can be used to derive test parameters.

Breathing machine test conditions are normally defined in terms of the following physiological parameters:-

(i) respiratory minute volume (pulmonary ventilation);
(ii) tidal or stroke volume;
(iii) breathing rate;
(iv) CO_2 content of the exhaled air.

Physiological studies show that these parameters are interrelated and that they exhibit characteristic patterns of response when physical work is undertaken (ASMUSSEN, 1965; ASTRAND and RODAHL, 1977). It is clearly important to examine the quantitative basis of these relationships if the machine test conditions are to simulate the physiological responses to work.

3.2 Relationships between respiratory parameters during work

3.2.1 Respiratory gas exchange

During physical work, the energy requirements of the muscles are met by the body's metabolic processes. The oxygen required for metabolism must be extracted from the air in the lungs and then transported by the cardiovascular system to the active tissues. Similarly, carbon dioxide, a waste product of oxidative metabolism, must be eliminated essentially at the same rate as it is produced. These processes are regulated by cardiorespiratory mechanisms which act to maintain the body's chemical equilibrium.

In considering the relationships between the various respiratory parameters, a logical starting point is the metabolic cost of the work activity. The metabolic rate required to sustain work entails corresponding levels of oxygen uptake and carbon dioxide output. This in turn requires an appropriate rate of pulmonary ventilation, achieved through changes in tidal volume and respiratory rate.

3.2.2 Oxygen uptake and metabolic rate

A number of studies have shown that oxygen uptake (VO_2) is directly proportional to work intensity (ASMUSSEN, 1965; LANPHIER and CAMPORESI, 1982) and on this basis it has frequently been used to guide physical effort. Typical values range from around 0.3ℓ min^{-1} for an individual at rest through to 0.9 and 2.0ℓ min^{-1} for 'light' and 'heavy' industrial tasks, respectively.

Every individual has an upper limit of oxygen uptake which may be reached only during very heavy work involving major muscle groups. This maximum oxygen uptake (VO_2 max) is determined primarily by the capacity of the circulatory system to transport oxygen from the lungs to the working muscles, and is influenced by factors such as age, body size and physical fitness (ASMUSSEN, 1965).

Maximum oxygen uptake can only be sustained for a few minutes and is unlikely to be attained in industrial conditions. Maximal levels have been recorded, however, during firefighting and rescue tasks which involve the use of breathing apparatus (BENTLEY, 1980; LOUHEVAARA *et al*, 1986).

Metabolic rate and oxygen uptake are related by the metabolic energy equivalent. It has been found that for each litre of oxygen consumed about 21 kj* of metabolic energy is delivered (ASTRAND and RODAHL, 1977). This is the basis of the technique of indirect calorimetry, whereby measurements of respiratory oxygen uptake are used to determine matabolic rates for various activities (PASSMORE and DURNIN, 1955; CONSOLAZIO *et al*, 1962).

3.2.3 Carbon dioxide output

Carbon dioxide is produced as an end product of oxidative metabolism during exercise. The output of carbon dioxide (VCO_2) is closely related to the uptake of oxygen, this relationship being expressed by the respiratory quotient, RQ;

$$RQ = \frac{CO_2 \text{ production } (\ell \text{ min}^{-1})}{O_2 \text{ consumption } (\ell \text{ min}^{-1})}$$

The value of the respiratory quotient is determined by the substrate being metabolised and ranges from 0.7 for fats to 1.0 for carbohydrates (ASMUSSEN, 1965).

The respiratory quotient varies with work intensity (LANPHIER and CAMPORESI, 1982). At rest or during moderate physical activity, RQ has a value of about 0.8 for an individual on a normal mixed diet. During heavy physical work, however, RQ approaches and may even exceed unity.

MORRISON and REIMERS (1982) have published an empirical relationship for the determination of RQ in diving tasks. This may be unsuitable for an industrial population, however, and could underestimate CO_2 output for some workloads. For the purposes of deriving machine test parameters it is probably safest to assume that carbon dioxide production equals oxygen uptake, i.e. RQ = 1.

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* This is equivalent to a metabolic rate of 350W for an oxygen uptake of 1ℓ min^{-1}.

3.2.4 Respiratory minute volume (pulmonary ventilation)

The increases in oxygen uptake and carbon dioxide output which accompany physical exertion necessitate a corresponding increase in pulmonary ventilation (V_E). On transition from rest to exercise, ventilation increases rapidly eventually achieving a steady state at a level dependent on the intensity of work (ASMUSSEN, 1965).

When plotted against oxygen uptake, pulmonary ventilation exhibits an almost linear relationship for light to moderately heavy workloads (up to oxygen uptakes of 2.5 to 3.0ℓ min^{-1}). Typically pulmonary ventilation is about 25-30ℓ min^{-1} (BTPS)* per litre of oxygen consumed at rest or during light to moderately heavy work. When VO_2 exceeds 2.5 to 3.0ℓ min^{-1}, pulmonary ventilation increases to about 30-35ℓ min^{-1} per litre of oxygen consumed (ASTRAND and RODAHL, 1977). There is, however, considerable variation between individuals in the pulmonary ventilation attained for a given oxygen uptake. Factors such as age, physical fitness and type of task all influence the ventilation response (DURNIN and EDWARDS, 1955; LIDDELL, 1963; BERNARD *et al*, 1979a).

For the purposes of establishing test parameters, several empirical relationships between V_E and VO_2 can be considered. COTES (1979) suggests the following predictive formula for healthy adult males undertaking exercise with the legs (bicycle ergometer or treadmill exercise):-

$$V_{E(BTPS)} = 22\ VO_{2(STPD)} + 2.$$

This relationship accords well with published data for industrial subjects (BERNARD *et al*, 1979b). A simpler approximation, $V_{E(BTPS)} = 24\ VO_{2(STPD)}$ has been suggested by some authors (WILKIE, 1968; KERSLAKE, 1972) and indeed has been quoted in a draft CEN standard for the selection and use of RPE. It is proposed to use this simpler formulation in the derivation of test parameters.

3.2.5 Respiratory frequency and tidal volume

The increase in pulmonary ventilation which accompanies muscular exercise results from changes in respiratory frequency (f) and tidal volume (V_t). For light to moderate workloads, increased ventilation is achieved initially by increasing tidal volume, respiratory frequency showing a less marked response (ASMUSSEN, 1965). Increases in respiratory frequency became more apparent when oxygen uptake exceeds 2.0ℓ min^{-1}.

Tidal volume is thus scaled to pulmonary ventilation, increasing with increasing workload. Again the relationship varies between individuals, factors such as gender, health status and ethnic origin having an influence (COTES, 1979). The following empirical

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* It is conventional to express pulmonary ventilation at body temperature and pressure saturated with water vapour (BTPS). VO_2 and VCO_2 are usually reduced to STPD.

relationship has been derived by HEY *et al* (1966) and can be used to predict V_t during exercise and CO_2 breathing.-

$$V_e = 28\ (V_t - 0.32)\ \ell\ min^{-1}.$$

As the relationship appears to fit a wide range of experimental data (HEY *et al*, 1966) it is proposed to use this to scale machine tidal volume to the respiratory minute volume.

3.3 Derivation of machine test parameters

3.3.1 Metabolic rate data

As a first step in deriving machine test parameters, the range of metabolic rates for industrial tasks must be defined. The tasks undertaken while wearing RPE reflect the full spectrum of industrial activity from light inspection duties through to the heavy manual workloads such as one found in mining or agriculture. Although mechanisation has reduced the requirement for manual effort in many industries, heavy tasks still remain, often associated with activities such as cleaning and maintenance of machinery. Heavy tasks are also prevalent in rescue or firefighting work. It is important, therefore, that the upper limit of metabolic rate should be carefully defined with due regard to the maximal physiological demands likely to be made on RPE by wearers.

The indirect calorimetric method described in Section 3.2.2 has been used by physiologists to produce an extensive data base on the metabolic rates associated with various industrial tasks. The bulk of this information derives from field studies conducted in the 1950s (e.g. LEHMANN *et al*, 1950; PASSMORE and DURNIN, 1955). More recent studies tend to be more restricted in scope, covering specific occupational groups or work activities (e.g. mining tasks, BOBO *et al*, 1983). Much of the available data have been summarized in a recent draft international standard for the determination of metabolic rate, ISO/DIS 8996 (INTERNATIONAL ORGANISATION FOR STANDARDISATION, 1987).

Although the draft standard covers a comprehensive range of occupational activities it does not contain data specific to workers using RPE. Indeed there is a general lack of data on the physiological responses of RPE wearers under field conditions (LOUHEVAARA *et al*, 1985). The draft standard can be used to categorise RPE wearers' metabolic rates, however, if the following premises are accepted:-

(i) Metabolic rates for a given task show considerable variation (~ 20%) depending on factors such as working method, pace and skill of the individual doing the work (PASSMORE and DURNIN, 1955; ASTRAND and RODAHL, 1977; ISO/DIS 8996. Against this background, the relatively small effects of RPE (excluding breathing apparatus) on metabolic cost (LOUHEVAARA, 1984) can be neglected.

(ii) The effects of factors such as breathing resistance and dead space are, to some extent, incorporated in published data. The indirect calorimetric method requires the subject to wear a face mask or mouthpiece so that exhaled air may be collected (FORD and HELLERSTEIN, 1959).

3.3.2 Categorisation of metabolic rates for tasks involving the use of RPE

ISO/DIS 8996 proposes a classification of metabolic rates for industrial tasks and this is shown in Table 2.

The five metabolic rate categories in Table 2 cover activities from rest (65 Wm^{-2}) through to heavy work such as shovelling (290 Wm^{-2}).

Although the classification appears to cover a representative range of industrial workloads it does not cover some of the heavier tasks for which RPE are worn. During firefighting and rescue work with self-contained breathing apparatus, average metabolic rates in the range 410-550 Wm^{-2} have been recorded (LOUHEVAARA *et al*, 1985). Furthermore, peak metabolic rates may approach 740 Wm^{-2} during simulated escape from underground workings using closed circuit breathing apparatus (BENTLEY and BOSTOCK, 1981). These metabolic rates clearly exceed the maximum benchmark of 290 Wm^{-2} (class 4) and support the retention of existing test parameters for breathing apparatus.

The limited data available, however, suggest that the ISO classification is suitable for establishing test parameters for respirators and air fed equipment. LOUHEVAARA *et al* (1985) have measured metabolic rates in the range 100 to 330 Wm^{-2} for workers wearing half mask dust respirators on construction sites. Similar values were obtained by the same authors for workers wearing airline apparatus (half and full face mask, demand type) in foundries and shipyards. For air fed suits used in the nuclear industry, metabolic rates have been found to be in the range 70-270 Wm^{-2} (ROWLANDS, 1966; Unpublished IOM data, 1987).

3.3.3 Derivation of respiratory parameters from metabolic rate data

The various relationships between respiratory variables described in Section 3.2 can be used to derive test conditions based on the ISO metabolic rate classification. Table 3 lists respiratory parameters for each metabolic rate class derived as follows:-

(i) Oxygen uptake is determined from metabolic rate using the energy equivalent, 1ℓ O_2/min = 350W (195 Wm^{-2}).

(ii) Respiratory minute volume (pulmonary ventilation) is then estimated from $V_{E(BTPS)} = 24\ VO_{2(STPD)}$.

(iii) Carbon dioxide output is assumed to be equivalent to oxygen uptake, i.e. RQ = 1.

(iv) Tidal volume is obtained from $V_E = 28\ (V_t - 0.32)$.

Table 2 Classification of metabolic rate from ISO/DIS 8996

Class	Value to be used for calculation of mean metabolic rate W/m² *	W	Examples
0 Resting	65	115	Resting
1 Low metabolic rate	100	180	Sitting at ease; light manual work (writing, typing, drawing, sewing, book-keeping); hand and arm work (small bench tools, inspection, assembly or sorting of light materials); arm and leg work (driving vehicle in normal conditions, operating foot switch or pedal); Standing; drilling (small parts); milling machine (small parts); coil winding; small armature winding; machining with low power tools; casual walking (speed up to 3.5 km/h).
2 Moderate metabolic rate	165	295	Sustained hand and arm work (hammering in nails, filing); arm and leg work (off-road operation of lorries, tractors or construction equipment); arm and trunk work (work with pneumatic hammer, tractor assembly, plastering, intermittent handling of moderately heavy material, weeding, hoeing, picking fruits or vegetables, pushing or pulling light-weight carts or wheelbarrows, walking at a speed of 3.5 to 5.5 km/h, forging).
3 High metabolic rate	230	415	Intense arm and trunk work; carrying heavy material; shovelling; sledgehammer work; sawing; planing or chiselling hard wood; hand mowing; digging; walking at a speed of 5.5 to 7 km/h. Pushing or pulling heavily loaded hand carts or wheelbarrows; chipping castings; concrete block laying.
4 Very high metabolic rate	290	520	Very intense activity at fast to maximum pace; working with an axe, intense shovelling or digging; climbing stairs, ramp or ladder; walking quickly with small steps; running; walking at a speed greater than 7 km/h.

* Metabolic rate data are based on a standard person with physical characteristics as shown below:-

	Men	Women
Height (m)	1.7	1.6
Weight (kg)	70	60
Body surface area (m^2)	1.8	1.6
Age (y)	35	35

(v) Respiratory frequency is given by V_L/V_t.

Clearly it would not be feasible, or indeed particularly informative, to test respirators at all five levels shown in Table 3. It is proposed therefore that test conditions are restricted to classes 0, 2 and 4. Some adjustment of the parameters is also necessary to facilitate the setting of the breathing machine. Suggested test conditions are given in Table 4.

In conclusion, it can be stated that the proposed test parameters have the following advantages over the majority of those listed in Chapter 2. Firstly, they are based on metabolic rate benchmarks which will eventually become part of an internationally recognised standard. The metabolic rate classes are also representative of a broad range of modern industrial conditions.

Secondly, the breathing machine parameters are scaled to physiological data and reflect respiratory responses to increasing workload. This ensures that test conditions go some way towards simulating the demands made on RPE by human wearers.

One important limitation of breathing machine tests must be recognised, however. In human wearers the respiratory pattern is often changed by the respirator, adaptive responses being made to increased breathing resistance and dead space (LOUHEVAARA, 1984). A machine test could not be expected to replicate these conditions and must be regarded simply as a screening procedure for potential dead space effects.

Table 3 Respiratory variables derived from ISO/DIS 8996 metabolic rate classification

ISO Class	Metabolic rate (Wm^{-2})	Oxygen uptake (ℓ min^{-1}) STPD	Carbon dioxide output (ℓ min^{-1}) STPD	Respiratory minute volume (ℓ min^{-1}) BTPS	Tidal volume (ℓ)	Respiratory frequency (min^{-1})
0	65	0.3	0.3	7	0.6	12
1	100	0.5	0.5	12	0.8	15
2	165	0.8	0.8	19	1.0	19
3	230	1.2	1.2	29	1.4	21
4	290	1.5	1.5	36	1.6	22

Table 4 Proposed test parameters for industrial RPE.

ISO Class	Target metabolic rate (Wm^{-2})	Carbon dioxide output (ℓ min^{-1})	Respiratory minute volume (ℓ min^{-1})	Tidal volume (ℓ)	Respiratory frequency (min^{-1})	Exhaled* CO_2 (%)
0	>65	0.4	7	0.5	14	5
2	>165	1.0	20	1.0	20	5
4	>290	1.8	36	1.5	24	5

* Exhaled CO_2 concentration fixed at 5% so that a standard gas mixture may be used to feed the breathing machine.

4. TOLERANCE LIMITS FOR INHALED CARBON DIOXIDE IN RPE

4.1 Scientific basis for test criteria

Having established a physiological rationale for deriving test parameters, it is necessary to consider further the question of performance criteria. Although many of the existing test methods have adopted a limit value of 1% carbon dioxide in the inhaled air, some authors (e.g. VERCRUYSSEN and KAMON, 1984) have argued for higher limits in certain special circumstances, e.g. breathing apparatus used by trained rescue personnel. For respirators used in industrial workplaces, however, it is essential that test methods 'screen out' devices which are likely to impose undue physiological strain on wearers. This means that the inhaled CO_2 limit must be set at a level which is safely tolerated by the majority of the industrial workforce during everyday work without adverse physiological effects or clinical symptoms. On this basis levels tolerated by trained and selected personnel may be inappropriate for an industrial population.

This chapter presents an overview of the literature on the effects of elevated carbon dioxide concentrations and considers the extent to which existing performance standards are supported by scientific data. In evaluating such data special consideration has been given to factors which, in RPE, may modify physiological responses. These include oxygen depletion, breathing resistance and high air inspired temperatures.

4.2 Physiological and health effects of elevated carbon dioxide levels

4.2.1 Physiological mechanisms

Carbon dioxide is a normal body constituent and has important physiological roles in the control of respiration and the regulation of cerebral blood flow (LAMBERTSEN, 1960). It is readily taken up by the blood and can freely diffuse into the body tissues, leading to a rapid onset of toxic effects (LAMBERTSEN, 1974; NATIONAL INSTITUTE OF OCCUPATIONAL SAFETY AND HEALTH, 1976).

When ambient levels exceed a threshold of about 0.3% CO_2, the partial pressure gradient from the blood to the lungs becomes less favourable to the elimination of metabolically generated carbon dioxide (MALKIN, 1975). The body initially compensates for this by increasing pulmonary ventilation. However, as inhaled CO_2 levels increase further (beyond 1-2%) the effectiveness of this response falls off, with the result that arterial CO_2 levels increase beyond their normal range, 35-45 mm Hg (LAMBERTSEN, 1974; LANPHIER and CAMPORESI, 1982). If unchecked, the consequent acidosis can cause severe disruption to acid-base regulation with widespread effects on the respiratory, circulatory and central nervous systems (MALKIN, 1975).

At concentrations in excess of 7.5%, carbon dioxide has a narcotic action leading to signs of intoxication and eventual loss of consciousness. While such levels are unlikely to be encountered in industrial RPE, they could be attained in the rare event of air supply failure in a positive pressure device (BOSTOCK, 1985).

The toxic effects of carbon dioxide are known to be related to the duration of exposure as well as the ambient concentration (KING, 1949). For example, an ambient level of 10% CO_2 can lead to the onset of neurological symptoms in less than two minutes (BROWN, 1930; DRIPPS and COMROE, 1947). On the other hand, concentrations in the range 1 to 1.5% have been tolerated for extended periods (up to 42 days) without adverse physiological effects or symptoms (EBERSOLE, 1960; HARRISON and SMITH, 1981). Indeed, during prolonged exposures at these levels there may be some adaptation or acclimatization which can modify the physiological and biochemical changes (CHAPIN *et al*, 1955; SCHAEFER *et al*, 1963).

4.2.2 Acute exposure limits

Considerable research effort has been directed at the problem of defining permissible exposure limits for carbon dioxide (GLATTE and WELCH, 1967; CLARK, 1973; MALKIN, 1975; NATIONAL INSTITUTE OF OCCUPATIONAL SAFETY AND HEALTH, 1976). Much of this interest derives from the operational difficulties created by carbon dioxide accumulation in submarines and spacecraft (SCHULTE, 1964; ROTH, 1968).

Research data have been accumulated covering both short-term (acute) and long-term (chronic) exposures to elevated carbon dioxide levels (GLATTE and WELCH, 1967). Acute exposure data are most relevant to industrial RPE since periods of continuous wear are unlikely to exceed several hours.

Table 5 summarises data on acute exposure from several sources. It can be seen that toxic effects range from barely detectable increases in pulmonary ventilation to loss of consciousness and convulsions, depending on the concentration inhaled. Effects on work performance and efficiency are also important from the viewpoint of industrial safety and have therefore been included in the Table.

In interpreting the exposure data a number of caveats should be borne in mind. Firstly, there is considerable variation between individuals in the magnitude of physiological response to a given carbon dioxide level (SCHAEFER, 1958; LAMBERTSEN, 1960; MILIC-EMILI, 1975). Furthermore, this variability becomes greater with increasing inhaled carbon dioxide levels (LAMBERTSEN, 1960). In practice this means that some individuals may have a lower threshold for the onset of symptoms such as headache and breathlessness (SCHAEFER, 1963).

A further point to consider is that much of the exposure data derives from experiments on healthy male subjects, usually military personnel (ROTH, 1968). Such data must be applied with caution to an industrial population where there may be a wider spread of physical capabilities (JAMES, 1976).

Table 5 Acute effects of carbon dioxide.

CO_2 level (%)	PHYSIOLOGICAL EFFECTS	SYMPTOMS	PERFORMANCE CHANGES	SOURCES
<0.3	N	N	N	MALKIN, 1975 GUILLERM and RADZIZSEWSKI, 1979
0.5-0.8	No significant physiological response.	N	N	SCHAEFER, 1961
1	Mild increase in pulmonary ventilation may occur, but no adverse physiological effects.	N	No loss in efficiency. Maximal work possible.	GLATTE and WELCH, 1967 MENN *et al*, 1970 PINGREE, 1973
1.5	Increase in pulmonary ventilation (c. 30%). No adverse physiological effects when moderate work undertaken.	Symptoms of headache and breathlessness may be experienced during heavy work.	No performance degradation.	ROTH, 1968 CLARK, 1973 SUSNIK, 1979
2	Increased pulmonary ventilation (c. 50%) and slight acidosis at rest. No adverse physiological changes during moderate work but metabolic acidosis becomes limiting in heavy work.	Headaches may develop after several hours. Breathlessness on exertion. Subjects aware of increased breathing rate.	Reduced capacity for heavy work, but no loss in mental efficiency.	SCHULTE, 1964 MENN *et al*, 1970 LEERS, 1972 LUFT *et al*, 1974 MALKIN, 1975
3	Increased pulmonary ventilation (2 x resting level) and acidosis.	Many subjects experience:- headache, breathlessness, dizziness, sweating. Aware of increased rate and depth of breathing.	Some loss of efficiency in skilled tasks. Difficulty in performing moderate work.	SCHULTE, 1964 SCHAEFER, 1963 SINCLAIR *et al*, 1971 CLARK, 1973 MALKIN, 1975 LOVE *et al*, 1979
5	Increased pulmonary ventilation (3 x resting level) and acidosis. Increases in heart rate and blood pressure.	Symptoms as above, increase in severity. Chest muscle pain. Visual disturbances, disorientation and excessive fatigue.	Mental depression and performance degradation. Light work difficult.	SCHULTE, 1964 CLARK, 1973 MALKIN, 1975
7.5	Increased pulmonary ventilation and acidosis. Cardiovascular effects with possible disturbance of cardiac rhythm. CNS disturbances including loss of consciousness in some subjects.	Severe sensory disturbances, sweating, dizziness, muscle tremor.	Physical work impossible. Severe impairment of mental performance.	BROWN, 1930 DRIPPS and COMROE, 1947 SECHZER *et al*, 1960 SCHAEFER, 1963 GLATTE and WELCH, 1967 ROTH, 1968
10	Severe CNS disturbances. Rapid loss of consciousness in nearly all subjects.	Severe distress including loss of muscle control and convulsions.	Severe impairment. Unable to take steps to preserve life.	BROWN, 1930 SECHZER *et al*, 1960 ROTH, 1968

N = No effects detected.

Finally, due account must be taken of the effects of physical work. A number of studies (MENN *et al*, 1970, LUFT *et al*, 1974, SUSNIK, 1980) have shown that physiological responses to elevated carbon dioxide levels are augmented by exercise. An individual's resistance to the toxic effects of carbon dioxide may therefore decrease with increasing workload (MALKIN, 1975). Physical work capacity may also diminish considerably as ambient CO_2 levels exceed 2% (see Table 5).

Returning to the issue of RPE standards, the data in Table 5 appear to strongly reinforce the 1% inhaled carbon dioxide limit. Although there is a mild increase in pulmonary ventilation (c 10%, GUILLERM and RADZISZEWSKI, 1979) at this level, there is little likelihood of adverse physiological effects or symptoms. Maximal physical effort, such as might be required in emergency egress, is also possible.

The 1.5% inhaled CO_2 limit specified in prEN 145 and in Parts 2 and 3 of BS 4667 may be less appropriate for an industrial RPE standard. Although no adverse physiological effects are likely to occur during moderate work, some individuals may experience symptoms of headache and breathlessness during heavy workloads. There is no evidence of lasting health effects or performance degradation at 1.5% CO_2 (ROTH, 1968), however, so this could be considered as an upper limit for medically screened workers (NATIONAL SAFETY COUNCIL, 1980). Given too, that physiological reactions take several minutes to develop (KING, 1949), short-term exposures to 1.5% CO_2 may be tolerated safely provided that the average inhaled level does not exceed 1%.

Reports of symptoms, particularly in association with physical work become more prevalent at carbon dioxide concentrations in excess of 2.0%. Work capacity also suffers a progressive reduction. On this basis the limit value of 2% adopted in some of the published methods for RPE (KLOOS and LAMONICA, 1966; LEERS, 1972) can be questioned. Indeed, KLOOS and LAMONICA conceded in their report that BA wearers would experience discomfort at this level if sets were worn for two hours or more.

An inhaled level of 3% CO_2 would appear to be the upper limit, even for emergency devices. Beyond this level an individual's ability to escape from the workplace could be considerably hampered by reduced work capacity due to the effects of increased pulmonary ventilation and carbon dioxide retention (MALKIN, 1975).

4.2.3 Effects of oxygen depletion, breathing resistance and high air temperatures

In face masks or air fed hoods, carbon dioxide build-up is generally accompanied by oxygen depletion, a factor which may augment the wearer's ventilatory response (ASMUSSEN and NEILSEN, 1957). Experimental studies (DILL and ZAMCHECK, 1940; SHOCK and SOLEY, 1942; SCHAEFER, 1959) suggest, however, that oxygen levels must fall well below 16% before there is a marked increase in pulmonary ventilation. It can be concluded that at the levels of carbon dioxide accumulation found in industrial RPE (<2%, JAMES, 1976), oxygen depletion is unlikely to be a significant factor in response. This is borne out by the findings of SUSNIK (1980) who showed that

1.5% CO_2 was tolerated without adverse physiological effect in the presence of oxygen depletion to 19.5% CO_2.

The interactions between the effects of breathing resistance and respirator dead space are relatively well documented. Increases in both inhalation and exhalation resistance above normal airway levels can result in hypoventilation and carbon dioxide retention (LOUHEVAARA, 1984). This may be associated with a diminished ventilatory response to increased arterial CO_2 levels (CHERNIAK and SNIDAL, 1956; BRODOWSKY *et al*, 1960) and hence may result in less effective compensation. The effects on strain are demonstrated by the following studies.

CRAIG *et al* (1970) studied the combined effects of elevated breathing resistance (inhalation resistance 1.5-15.5 cm H_2O/ℓ/sec, exhalation resistance 2.0-3.9 cm H_2O/ℓ/sec) and carbon dioxide levels (1.1-4.5%) on subjects undertaking heavy physical work. It was found that for a given level of breathing resistance, work endurance time was reduced when the inhaled CO_2 level exceeded 3%.
LOVE *et al* (1979) examined the effects of 2 to 5% inhaled CO_2 on the ventilatory responses of mineworkers breathing through an inspiratory resistance of 10 cm H_2O (at 100 ℓ min^{-1}). Several subjects were unable to complete the treadmill workload (VO_2 ~ 1.6ℓ min^{-1}) when the inhaled CO_2 level was 4% or more, this being associated with symptoms of headache and breathlessness. The authors concluded that inhaled CO_2 levels in excess of 3% were unlikely to be tolerated by industrial workers. It was considered that above this level the combined effects of physical workload, breathing resistance and inhaled CO_2 would cause severe discomfort due to high levels of pulmonary ventilation and/or carbon dioxide retention.

The effects of high air temperatures on carbon dioxide tolerance are less well understood. Physiological studies (e.g. VEJBY-CHRISTENSEN and STRANGE PETERSEN, 1973) have shown that elevations in body temperature increase the ventilatory response to carbon dioxide. ROSS (Personal Communication) found, however, that a hot environment (45^{0}C, DB) had no effect on the ventilatory response to 5% CO_2 during exercise at 100 W. More recent work by BABB *et al* (1989) indicates that there may be a reduction in the ventilatory response when hot air (45^{0}C, DB, 95% RH) is breathed. Clearly there is a need for further experimental work in this area before the effects of elevated temperatures can be defined.

Taken together, the available research findings, suggest that the 1% CO_2 inhalation limit need not be modified to allow for the effects of oxygen depletion, breathing resistance or high ambient temperatures. However, it should be recognised that these factors may exacerbate the effects of the elevated CO_2 levels (>3%) which may occur in smoke hoods or self-rescuers* in carbon monoxide atmospheres.

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* Devices which use a hopcalite filter to convert CO to CO_2.

4.3 Implications for RPE standards

The published data on the acute effects of CO_2 support the retention of the 1% inhaled CO_2 limit in RPE standards. At this level physiological compensatory mechanisms appear to be effective and symptoms are unlikely to be experienced by healthy individuals. Physical work capacity also remains relatively unaffected and mental performance does not appear to be impaired. A further safety factor lies in the fact that 1% CO_2 may be tolerated for prolonged periods without lasting effects on health (PINGREE, 1973).

Although it could be argued that physiological compensation is effective at CO_2 levels of up to 2% (JAMES, 1976), there is an increasing likelihood of symptoms being experienced. Given the variability in physiological response to CO_2 which exists within the general population (LAMBERTSEN, 1960; MILIC-EMILI, 1975), it seems sensible to set the inhaled limit below the reported threshold for the onset of symptoms (i.e. below 1.5% CO_2, see Table 5). This would meet the requirement that exposure should be limited to a level tolerated by the majority of the workforce, on an everyday basis, without adverse effects on health.

The progressive impairment of work capacity which occurs at inhaled levels in excess of 1.5% CO_2 also strengthens the case for the 1% limit. It is clearly important that an industrial respirator should not compromise the wearer's ability to escape from a hazardous situation.

Some comment should be made on the apparent discrepancy between the 1% limit in RPE standards and the long-term occupational exposure limit of 0.5% CO_2 for workroom air (HEALTH AND SAFETY EXECUTIVE, 1990). Given that RPE are not worn continuously for eight hours, it is unlikely that a device meeting the 1% standard would cause the exposure limit to be exceeded on the basis of a time weighted average. Periods of exposure to elevated CO_2 concentrations (>0.5%) would be offset by rest periods in ambient air (CO_2 concentration nominally 0.03%). However, where devices such as air fed full suits are worn for extended periods of time (say, more than four hours) there may well be a case for setting the inhalation limit below 1% CO_2. This would, of course, require that the test parameters proposed in Chapter 3 were used in the assessment.

5. RECOMMENDATIONS

The following recommendations are made concerning performance standards for inhaled carbon dioxide in respiratory protective equipment:-

(i) Breathing machine test parameters should be based on metabolic rate benchmarks which represent the range of metabolic cost for industrial tasks.

(ii) Devices should be tested at a number of machine settings based on graded metabolic rate levels. The following settings are suggested, derived from the draft international standard ISO/DIS 8996.

ISO Class	Target metabolic rate (Wm^{-2})	Carbon dioxide output (ℓ min^{-1})	Resp. minute volume (ℓ min^{-1})	Tidal volume (ℓ)	Resp. freq. (min^{-1})	Exhaled* CO_2 (%)
0	>65	0.4	7	0.5	14	5
2	>165	1.0	20	1.0	20	5
4	>290	1.8	36	1.5	24	5

* These settings are based entirely on theoretical considerations and require laboratory validation in order to determine their suitability for RPE standards.

(iii) The test parameters specified in some of the draft European standards (minute ventilation 50 ℓ min^{-1}, 5% CO_2 in exhalate) appear to be based on a metabolic rate level which exceeds the normal industrial range. It is proposed, however, that these test conditions are retained for RPE used under conditions of high physical workload, e.g. self-contained BA used in rescue and firefighting tasks.

(iv) The limit of 1% CO_2 in the inhaled air, specified by many RPE standards, is amply supported by scientific data and should be retained. CO_2 levels of 1.5 to 2%, while tolerated by medically fit personnel, are likely to result in a progressive impairment of work capacity and may be associated with the onset of clinical symptoms in susceptible individuals.

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